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Published in:

Proceedings of the National Academy of Sciences of the United States of America

DOI:

[10.1073/pnas.1722299115](https://doi.org/10.1073/pnas.1722299115)

Publication date:

2018

Licence:

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Document Version

Publisher's PDF, also known as Version of record

[Link to publication in Discovery Research Portal](#)

Citation for published version (APA):

Jonik-Nowak, B., Menneteau, T., Fesquet, D., Baldin, V., Bonne-Andrea, C., Méchali, F., Fabre, B., Boisguerin, P., de Rossi, S., Henriquet, C., Pugnière, M., Ducoux-Petit, M., Burlet-Schiltz, O., Lamond, A., Fort, P., Boulon, S., Bousquet, M-P., & Coux, O. (2018). PIP30/FAM192A is a novel regulator of the nuclear proteasome activator PA28y. *Proceedings of the National Academy of Sciences of the United States of America*, 115(28), E6477-E6486. [201722299]. <https://doi.org/10.1073/pnas.1722299115>

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PIP30/FAM192A is a novel regulator of the nuclear proteasome activator PA28 γ

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Edited by Alfred Lewis Goldberg, Harvard Medical School, Boston, MA, and approved May 29, 2018 (received for review December 21, 2017)

PA28 γ is a nuclear activator of the 20S proteasome involved in the regulation of several essential cellular processes, such as cell proliferation, apoptosis, nuclear dynamics, and cellular stress response. Unlike the 19S regulator of the proteasome, which specifically recognizes ubiquitylated proteins, PA28 γ promotes the degradation of several substrates by the proteasome in an ATP- and ubiquitin-independent manner. However, its exact mechanisms of action are unclear and likely involve additional partners that remain to be identified. Here we report the identification of a cofactor of PA28 γ , PIP30/FAM192A. PIP30 binds directly and specifically via its C-terminal end and in an interaction stabilized by casein kinase 2 phosphorylation to both free and 20S proteasome-associated PA28 γ . Its recruitment to proteasome-containing complexes depends on PA28 γ and its expression increases the association of PA28 γ with the 20S proteasome in cells. Further dissection of its possible roles shows that PIP30 alters PA28 γ -dependent activation of peptide degradation by the 20S proteasome in vitro and negatively controls in cells the presence of PA28 γ in Cajal bodies by inhibition of its association with the key Cajal body component coilin. Taken together, our data show that PIP30 deeply affects PA28 γ interactions with cellular proteins, including the 20S proteasome, demonstrating that it is an important regulator of PA28 γ in cells and thus a new player in the control of the multiple functions of the proteasome within the nucleus.

proteasome | PA28 γ | Cajal bodies | FAM192A | nuclear proteolysis

The 20S proteasome is a multimeric “barrel-like” protease that bears multiple peptidase (i.e., trypsin-like, caspase-like, and chymotrypsin-like) activities inside its internal catalytic chamber (1). It plays a major role in the regulated degradation of intracellular proteins and requires for its functioning, in most cases, the binding of regulatory complexes to one or both of its ends (1). Among these regulators, the well-characterized 19S regulatory complex has been shown to associate with the 20S core to form the 26S proteasome that specifically recognizes and degrades polyubiquitylated proteins (2, 3). Another type of 20S proteasome regulators is the PA28 (also called 11S or REG) family of complexes, which comprises in higher eukaryotes three related proteins (PA28 α , β , and γ) that associate in two distinct complexes (4). PA28 α and PA28 β form a cytoplasmic heteroheptamer, PA28 $\alpha\beta$ (5, 6), which participates in the immune response by favoring the generation of MHC class I antigens (7, 8). In contrast, PA28 γ is essentially nuclear and forms a homoheptamer (9, 10). PA28 complexes mediate primarily ubiquitin-independent proteolysis when bound to the 20S proteasome. However, they are also found in hybrid proteasomes (i.e., 20S proteasome bound to a PA28 heptamer on one end and a 19S complex on the other end) (11) and are thus likely to also participate in ATP-dependent degradation of ubiquitylated proteins.

Although PA28 γ has been little studied, it is involved in various essential cellular pathways, including cell proliferation,

through the degradation of the cell cycle inhibitors p21^{Cip1}, p16^{INK4A}, and p19^{Arf} (12–14). PA28 γ also participates in the Mdm2-dependent degradation of the tumor suppressor p53 (15). Furthermore, PA28 γ ^{−/−} mice display growth retardation (16) and PA28 γ is overexpressed in several types of cancer (17–19). In addition to its involvement in the control of cell proliferation, PA28 γ is implicated in the regulation of chromosomal stability (20) and plays important roles in nuclear dynamics by modulating the number and size of various nuclear bodies, including Cajal bodies (CBs) (21), nuclear speckles (22), and promyelocytic leukemia protein bodies (23). It is also involved in the cellular stress response, as it is recruited to double-strand break sites upon DNA damage (24) and is required for the UVC-induced dispersion of CBs (21).

Despite its important cellular functions, the mechanisms of action of PA28 γ , like those of the related PA28 $\alpha\beta$ complex, remain elusive. It is known that, like the 19S complex, PA28 complexes open the gated pore of the 20S proteasome’s α -ring upon binding, thus allowing easier substrate entrance into the catalytic chamber (25). Artificial peptide substrates commonly used to measure proteasome activities are believed to passively

Significance

The 20S proteasome is a key actor of the control of protein levels and integrity in cells. To perform its multiple functions, it works with a series of regulators, among which is a nuclear complex called PA28 γ . In particular, PA28 γ participates in the regulation of cell proliferation and nuclear dynamics. We describe here the characterization of a protein, PIP30/FAM192A, which binds tightly to PA28 γ and favors its interaction with the 20S proteasome while inhibiting its association with coilin, a central component of nuclear Cajal bodies. Thus, PIP30/FAM192A critically controls the interactome and, consequently, the functions of PA28 γ , and appears to be a previously unidentified player in the fine regulation of intracellular proteostasis in the cell nucleus.

Author contributions: O.B.-S., A.I.L., S.B., M.-P.B., and O.C. designed research; B.J.-N., T.M., D.F., V.B., C.B.-A., F.M., B.F., P.B., C.H., M.P., M.D.-P., P.F., S.B., M.-P.B., and O.C. performed research; S.d.R. contributed new reagents/analytic tools; B.J.-N., T.M., D.F., V.B., C.B.-A., F.M., B.F., P.B., C.H., M.P., M.D.-P., O.B.-S., A.I.L., P.F., S.B., M.-P.B., and O.C. analyzed data; and P.F., S.B., M.-P.B., and O.C. wrote the paper.

The authors declare no conflict of interest.

This article is a PNAS Direct Submission.

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This article contains supporting information online at www.pnas.org/lookup/suppl/doi:10.1073/pnas.1722299115/-DCSupplemental.

diffuse through the 20S pores, and therefore PA28s' stimulation of their degradation can be explained by 20S-pore opening only. However, how PA28 complexes recruit protein substrates and deliver them to the proteasome is not understood, as these complexes are a priori inert molecules that, unlike the 19S complex, do not possess any ATPase activity that could provide energy and movement to unfold the substrates and inject them into the 20S proteasome (2, 3). A likely possibility is thus that PA28 complexes function in proteasome-dependent proteolysis in association with other proteins that remain to be defined.

In this study, we describe a partner of a PA28 complex, the evolutionary conserved PIP30/FAM192A protein. We show that PIP30 binds with high specificity to PA28 γ and enhances its association with the 20S proteasome in cells. Importantly, PIP30 binding affects PA28 γ specificity toward peptide substrates in vitro as well as its interactions with cellular proteins, such as the CB marker coilin. Therefore, PIP30 is a major regulator of PA28 γ functions and consequently of the nuclear functions of the proteasome.

Experimental Procedures

Phylogenetic Analyses. Genomes were explored by using Annotation and BLAST search tools available in the Geneious 9.1.7 software package (www.geneious.com). Amino acid sequences were aligned (MAFFT v7.017) and a phylogenetic tree was deduced by maximum-likelihood analysis (PhyML).

Antibodies. Antibodies and related agents used in this study are described in *SI Appendix, Material and Methods*.

Production of 20S Proteasome and Recombinant Proteins. Native 20S proteasome was purified from extracts of HeLa cells (Ipracell) using classic chromatographic procedures (26). Unless indicated, recombinant PIP30 was produced in *Escherichia coli* BL21 DE3 CodonPlus as a 6His-tagged protein and purified by affinity purification followed by proteolytic removal of the tag, anion-exchange chromatography, and gel filtration (*SI Appendix, Fig. S10B*). At the last step, the protein was eluted slightly earlier than the BSA (67 kDa) marker (i.e., at an apparent molecular weight larger than twice what was expected). Human recombinant PA28 $\alpha\beta$ was produced and purified from *E. coli*, as previously described (27). Human PA28 γ was expressed in *E. coli* BL21 DE3 CodonPlus. After expression, the PA28 γ complex was purified by chromatography as PA28 $\alpha\beta$, with some minor modifications of the procedure. Both PA28 $\alpha\beta$ and PA28 γ complexes efficiently activated the peptidase activities of the 20S proteasome. Recombinant GST and GST-PIP30-H201 fusion proteins were produced in bacteria and efficiently purified using glutathione Sepharose beads.

Pull-Down and Immunoprecipitation. For immunoprecipitation (IP) of GFP-fusion proteins, U2OS cells were transfected with the indicated constructs. Twenty-four hours posttransfection, cells were homogenized in lysis buffer [25 mM Hepes pH 7.8, 100 mM KCl, 10 mM MgCl₂, 1 mM EDTA, 1% IGEPAL CA-630, 0.1% Triton X-100, 1 mM DTT, 1 mM ATP, 10% glycerol (vol/vol)], in the presence of complete EDTA-free protease inhibitor mixture (Roche), for 15 min on ice. After centrifugation at 15,000 $\times g$ for 15 min (4 °C), supernatants were recovered and protein concentration was determined by Bradford assays using BSA as a standard. Next, 20 μ L of GFP-TRAP-A beads (Chromotek) were used per IP, mixed with 200 μ g of protein extract, and incubated with constant gentle stirring for 1 h at 4 °C. Beads were washed three times with lysis buffer and boiled in 2 \times Laemmli sample buffer. Samples were then analyzed by SDS/PAGE and immunoblotting.

Endogenous PIP30 and PA28 γ were immunoprecipitated from total cell extracts using anti-PIP30 (rabbit) and anti-PA28 γ (rabbit) antibodies, bound to protein A magnetic beads (Dyna) for 2 h at 4 °C.

For co-IP of coilin and PA28 γ proteins (see, for example, Fig. 5B), nuclear extracts were prepared as described in ref. 21. Briefly, U2OS and PIP30^{-/-} cell pellets were resuspended in hypotonic buffer (10 mM Tris-HCl pH 7.5, 10% glycerol, 4 mM DTT, 50 mM NaF, 1 mM Na₃VO₄, 1 mM MgCl₂) in the presence of complete EDTA-free protease inhibitor mixture (Roche). IGEPAL CA-630 was then added at the final concentration of 0.5% and cells were incubated on ice for 3 min. After centrifugation at 800 $\times g$ for 5 min, the nuclei, present in the pellet, were resuspended in digestion buffer (2 mM Tris-HCl pH 8.5, 20% glycerol, 10 mM DTT, 50 mM NaF, 1 mM Na₃VO₄, 1 mM MgCl₂, 5 mM CaCl₂, 1 \times complete protease inhibitor mixture) supplemented with 75 U/mL micrococcal nuclease, and then digested for 15 min at 25 °C with constant stirring. At the

end, an equivalent volume of extraction buffer (2 mM Tris-HCl pH 8.5, 50 mM NaF, 1 mM Na₃VO₄, 1 mM MgCl₂, 20 mM EDTA, 0.84 M KCl, 1 \times complete protease inhibitor mixture) was added and the mix was incubated on ice for 20 min. Nuclear extracts were clarified by centrifugation for 30 min at 15,000 $\times g$. Before IP, KCl concentration was reduced to 280 mM, 3 μ g of anti-coilin or control IgG were added to 400 μ g of nuclear extracts and incubated for 2 h at 4 °C. IP proteins were collected by addition of 15 μ L of protein A-Sepharose beads. After extensive washes, beads were boiled in 2 \times Laemmli sample buffer and samples were analyzed by SDS/PAGE and immunoblotting.

Mass Spectrometry Analyses. Stable isotope labeling by amino acids in cell culture (SILAC) IPs (endogenous PA28 γ and GFP-FAM192A/PIP30) were essentially performed as previously described in ref. 28. Further details are provided in *SI Appendix*.

Whole human proteasome complexes, including 20S-bound activators and regulators, were immunopurified and analyzed by quantitative mass spectrometry, as previously described (29, 30). Next, 2 $\times 10^8$ in vivo formaldehyde-cross-linked human cells (HeLa and U937, three biological replicates per cell line) were used. For complete nuclear proteasome interactome analysis, U937 cells nuclei were prepared and, before proteasome purification, the purity of nuclear proteins was assessed both by Western blot and MS analysis, as detailed earlier (31). Purified proteasome complexes were analyzed by mass spectrometry as previously described (32). Further details are provided in *SI Appendix* section.

Native Electrophoresis in Tris-Glycine System. Recombinant protein samples were incubated 5–10 min at room temperature in reaction buffer [Tris-HCl 20 mM, pH 7.5, DTT 1 mM, Glycerol 10% (vol/vol)], then supplemented with 1 μ L of native sample buffer (xylene cyanol FF in reaction buffer supplemented with 50% glycerol) and applied on 5% polyacrylamide gel prepared in Tris-Glycine electrophoresis buffer (25 mM Tris-HCl pH 8.0, 192 mM Glycine, 1 mM DTT). Native electrophoresis was performed for 4–5 h (100 V, 4 °C). After denaturation in 10 \times TG-SDS buffer, proteins were transferred on PVDF membrane and immunoblotted.

Surface Plasmon Resonance Analysis. Experiments were performed on Biacore 3000 apparatus (GE Healthcare) at 25 °C using a flow rate of 50 μ L/min in HBS-EP buffer (GE Healthcare). To compare the binding of PA28 γ and PA28 $\alpha\beta$ on 6His-PIP30 recombinant protein, 6His-PIP30 (4500RU) was captured on anti-His-Tag covalently immobilized on a CM5 sensor chip using an amine coupling procedure according to the manufacturer's instructions. A control flowcell was obtained with the same chemical procedure without protein. Then, 60 μ L of PA28 γ and PA28 $\alpha\beta$ (50 μ g/mL) were injected on His6PIP30 and control flowcells followed by a dissociation step of 400 s.

In Vitro CK2 Phosphorylation Assay. GST and GST-PIP30-H201 proteins were incubated with recombinant CK2 according to the manufacturer's instructions. For radioactive kinase assays, ³³P labeled ATP (1 μ Ci in the presence of 100 μ M cold ATP) was included. Reactions were stopped either by adding 5 mM EDTA or Laemmli sample buffer.

Proteasome Peptidase Assays. Peptidase activities of 20S proteasome were measured using black flat-bottom 96-well plates (Nunc), in a final volume of 50 μ L, in reaction buffer [20 mM Tris-HCl pH 7.5, 50 mM NaCl, 1 mM DTT, 10% glycerol (vol/vol)] supplemented with 100 μ M peptide substrates. When indicated, purified recombinant PA28 and/or PIP30 were added. Kinetic analyses showed that the assays are linear at least for 30 min. Peptide degradation was measured by the fluorescence emitted by the AMC group released by cleavage of the substrate (excitation 380 nm, emission 440 nm) using a FLX800 microplate fluorescence reader (Bio-Tek Instruments).

Immunofluorescence Microscopy and Proximity Ligation Assays. Cells were fixed in 3.7% paraformaldehyde/PBS for 10 min at room temperature, washed with PBS and permeabilized in PBS containing 1% Triton X-100 for 15 min at room temperature. Coverslips were then blocked in blocking solution (1% FCS, 0.01% Tween-20/PBS) for 10–20 min and incubated with primary antibodies, diluted in blocking buffer, for 1 h at room temperature or 37 °C in a humidified atmosphere. After three washes in PBS, coverslips were incubated with Alexa-Fluor conjugated secondary antibodies diluted in blocking solution for 40 min at room temperature. Coverslips were washed with PBS, incubated with 0.1 μ g/mL DAPI solution in PBS for 5 min at room temperature, washed twice in PBS, and finally once in H₂O. Coverslips were mounted on glass slides using ProLong Gold antifade reagent (Thermo Fisher Scientific).

For proximity ligation assays (PLA), cells on coverslips were fixed and permeabilized as described in ref. 22. Coverslips were then blocked in a

solution provided by the Duolink kit. Cells were then incubated with mentioned antibodies as described above. Duolink In Situ PLA Probe Anti-Rabbit MINUS and Anti-Mouse PLUS and Duolink In Situ Detection Reagents (Sigma-Aldrich) were used, according to the manufacturer's instructions.

Image Acquisition and Analysis. The z-stacks and images were acquired with a 63×/1.4 NA or 40× oil-immersion objective lenses using widefield microscopes, DM6000 (Leica Microsystems) or Axioimager Z1 or Z2 (Carl Zeiss), equipped with coolSNAP HQ2 cameras (Photometrics). Images were acquired as TIF files using MetaMorph imaging software (Molecular Devices). For CB and PLA dot quantitative analysis, z-stacks were acquired every 0.3–0.4 μm (z-step) with a range of 10–15 μm to image the whole nuclei. The number of PLA foci was analyzed with ImageJ. The size, the intensity, and the number of CBs were measured with ImageJ (1.49v), using a specific “macro” that has been created to automatically quantify these different parameters. The script allows creating a mask of DAPI image to isolate the nucleus of each cell and create a maximum-intensity projection of the 25 z-stacks. The mask is used in the maximum-intensity projection to count the number of CB or PLA dots of each nucleus via an appropriate thresholding. The “Analyze Particles” tool of ImageJ was used to calculate the size and the mean gray value of each CB.

Results

FAM192A Is a Partner of both Free and 20S Proteasome-Bound PA28 γ That Regulates the Interaction Between PA28 γ and 20S Proteasome.

To identify new interactors of PA28 γ , we used a high-throughput approach combining endogenous PA28 γ IP and SILAC-based quantitative proteomics (28) (*SI Appendix, Fig. S1A, Left*). In this experiment, 68 human protein groups containing at least two unique peptides were quantified and visualized by plotting $\log_2[\text{heavy/light (H/L) ratio}]$ versus $\log_2(\text{H intensity})$ (Fig. 1A and *Dataset S1*). PA28 γ itself was found with a H/L SILAC ratio close to 15. Among the PA28 γ interactors was FAM192A, a poorly annotated nuclear protein of unknown cellular function, whose expression is induced during skeletal muscle atrophy (33). FAM192A was also identified with a high SILAC ratio in a GFP-PA28 γ pull-down that we performed in parallel (*Dataset S2*). Conversely, PA28 γ was the most abundant and almost unique partner pulled down with GFP-FAM192A (Fig. 1B and *SI Appendix, Fig. S1A, Right* and *Dataset S3*). Reciprocal IPs on endogenous proteins showed that at least 70% of each protein coprecipitates with the other (*SI Appendix, Fig. S1B*). Like PA28 γ , FAM192A is nuclear (*SI Appendix, Fig. S10A*) and interaction between the two proteins occurs within the nucleus (*SI Appendix, Fig. S1C*).

Using recombinant FAM192A and PA28 γ proteins produced in *E. coli*, we found that the interaction between FAM192A and PA28 γ is direct, as shown for example by native gel electrophoresis (Fig. 1C) or surface plasmon resonance (SPR) (*SI Appendix, Fig. S1D*). SPR showed no interaction between FAM192A and the closely related PA28 $\alpha\beta$ complex (*SI Appendix, Fig. S1D*), demonstrating the high specificity of PA28 γ /FAM192A interaction in vitro.

Through parallel approaches, we investigated putative nuclear proteasome interacting proteins by quantitative analysis of proteasome complexes immunopurified from nuclei of U937 cells using the MCP21 antibody (targeting the $\alpha 2$ subunit of 20S proteasome), as described previously (31). As expected, all 20S proteasome and 19S regulatory complex subunits, as well as known proteasome interactors, such as PA28 γ , PA200, and USP14, were found in this category [abundance ratios (IP 20S/IP control) above 2 and *P* value below 0.05 (*n* = 3)] (*SI Appendix, Fig. S2A* and *Dataset S4*). Interestingly, the protein FAM192A showed an enrichment factor of 6.4 and a *P* value $< 5 \times 10^{-4}$ and thus clearly qualifies as a proteasome interacting protein.

Further quantitative analysis of proteasome-associated proteins in HeLa cells showed that FAM192A is recruited on proteasomes in a PA28 γ -dependent manner (Fig. 1D), because it is absent in proteasome immunoprecipitates after PA28 γ knockdown. The enrichment in anti-FAM192A immunoprecipitates of all subunits of the 19S regulatory complex (PSMCx and

PSMDx) (*SI Appendix, Fig. S2B*) demonstrated that FAM192A is also recruited on hybrid proteasomes, most likely via its interaction with PA28 γ .

Interestingly, these experiments also showed that co-IP of PA28 γ with 20S proteasome was halved (*P* = 0.02) in siRNA FAM192A-depleted cells (Fig. 1D). This result was confirmed by reverse anti-PA28 γ co-IP experiments using wild-type and FAM192A^{−/−} U2OS cell extracts, showing that indeed FAM192A depletion elicits a twofold decrease in PA28 γ / $\alpha 4$ interaction (Fig. 1E). Thus, FAM192A promotes the association of PA28 γ with the 20S proteasome.

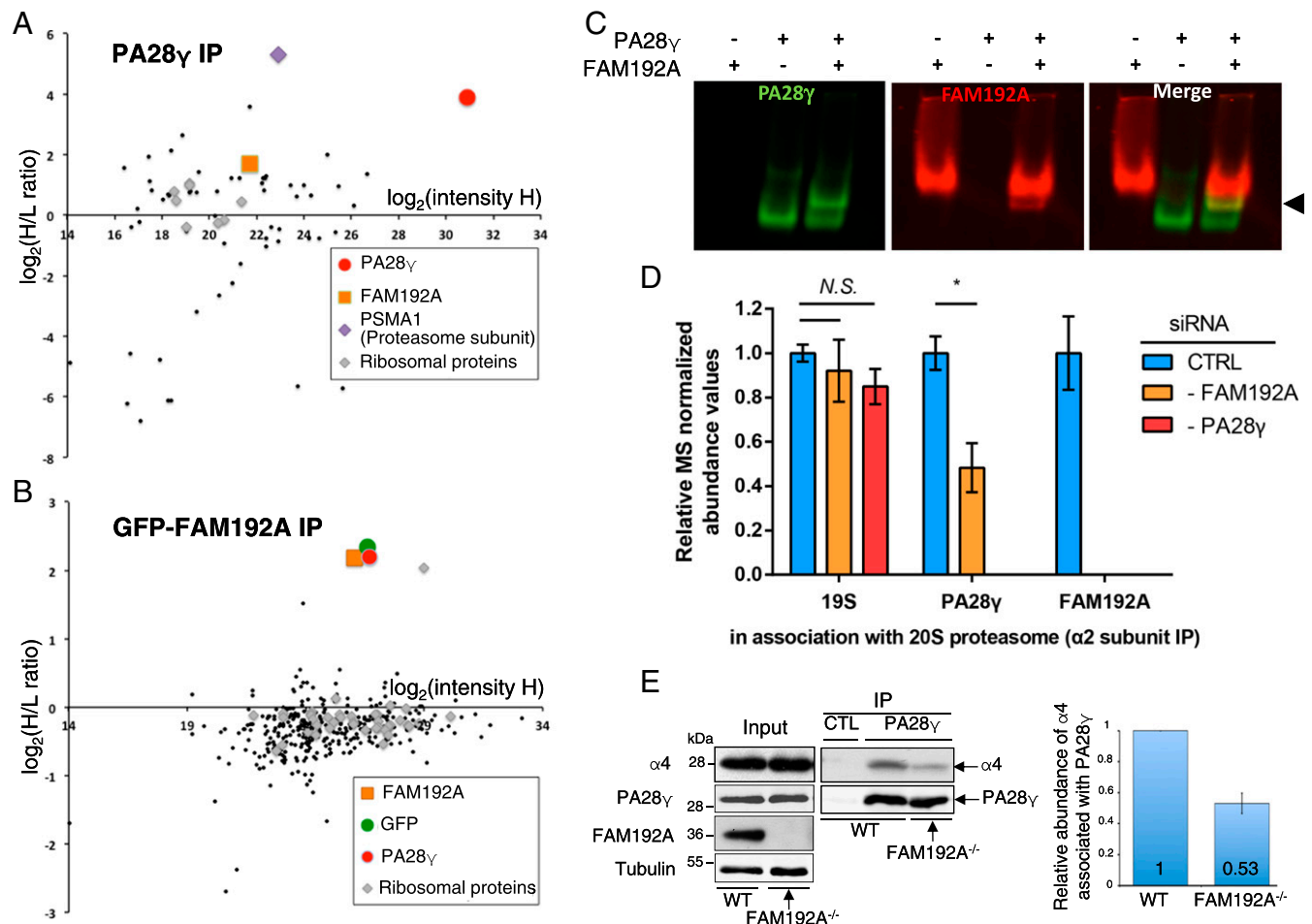
Altogether, our experiments establish that FAM192A is a major direct interactor of PA28 γ , recruited to proteasome complexes via PA28 γ and favoring the association of PA28 γ with the 20S proteasome. FAM192A is also called NIP30 (NEFA-interacting protein 30 kD), which might refer to a NIP-(4-hydroxy-5-iodo-3-nitrophenyl acetate) labeled 30-kD protein that interacts with phosphatidylinositol biphosphate (34). Based on the above experiments, and since FAM192A has no clear assigned cellular function, we propose to rename it PIP30, for PA28 γ interacting protein 30 kDa. This name will be used thereafter in this report.

PA28 γ /PIP30 Interaction Is Stabilized by CK2 Phosphorylation of PIP30 C Terminus. Evolutionary analyses show that the PIP30 sequence is characterized by the presence of three conserved domains: an N-terminal signature domain (pfam10187, also called NIP30 domain, ~100 amino acids) and two smaller motifs (*SI Appendix, Fig. S3A*). The pfam10187 domain is found in metazoa as well as in all major eukaryotic supergroups. This allows tracing back the PIP30 gene to early stages of eukaryote evolution (*SI Appendix, Fig. S3B*), as it is the case for PA28 γ (4). The conserved C-terminal motifs of PIP30 proteins are enriched in phosphorylatable residues, including a completely conserved tyrosine and several serine residues (*SI Appendix, Fig. S3A*).

Using various truncation mutants, we determined that the last 54 amino acids of PIP30 (amino acids 201–254; i.e., the H201 mutant) are necessary and sufficient for interaction with endogenous PA28 γ and that amino acids 223–230 are critical for the association (Fig. 2A and *SI Appendix, Fig. S4A and B*). This C-terminal region includes the highly conserved serine-rich and acidic sequence highlighted in *SI Appendix, Fig. S3A* and contains two SDSE motifs (*SI Appendix, Fig. S4C*) that both match the canonical consensus site (S/T-X-X-E/D/pS/pT) for casein kinase 2 (CK2) (35, 36). Indeed, we found that this region can be phosphorylated by CK2 in vitro (Fig. 2B). Phosphorylation is dependent on the integrity of the CK2 consensus sites, as it was reduced when the serine residues S₂₂₂ and S₂₂₈ were replaced by alanine (mutant SS-AA), and abolished or strongly impaired when the acidic residues within the two CK2 consensus motifs were converted into basic lysine residues (mutants D₂₂₃E₂₂₅-KK and D₂₂₉E₂₃₁-KK, respectively) (Fig. 2B).

In cells, in the context of the full-length GFP-PIP30 protein (Fig. 2C and *SI Appendix, Fig. S4D*), like in vitro with the C-terminal part of PIP30 (*SI Appendix, Fig. S4E*), these mutations altered the binding to PA28 γ . In a manner parallel to their effects on CK2 phosphorylation in vitro, the acidic mutants abolished or strongly impaired the binding to PA28 γ , while the SS-AA mutant reduced it (Fig. 2C and *SI Appendix, Fig. S4E*). The weaker binding of the SS-AA mutant strongly suggests that phosphorylation is stabilizing PA28 γ /PIP30 interaction. Indeed, when using purified proteins, PA28 γ showed more affinity for CK2-phosphorylated than for nonphosphorylated PIP30 (Fig. 2D).

To verify that CK2 is the endogenous kinase phosphorylating PIP30, we treated cells with the selective CK2 inhibitor CX-4945 (37). This treatment revealed a second, faster-migrating band (Fig. 2E), suggesting that in cells PIP30 is primarily in a CK2-phosphorylated form. This conclusion is strengthened by thorough



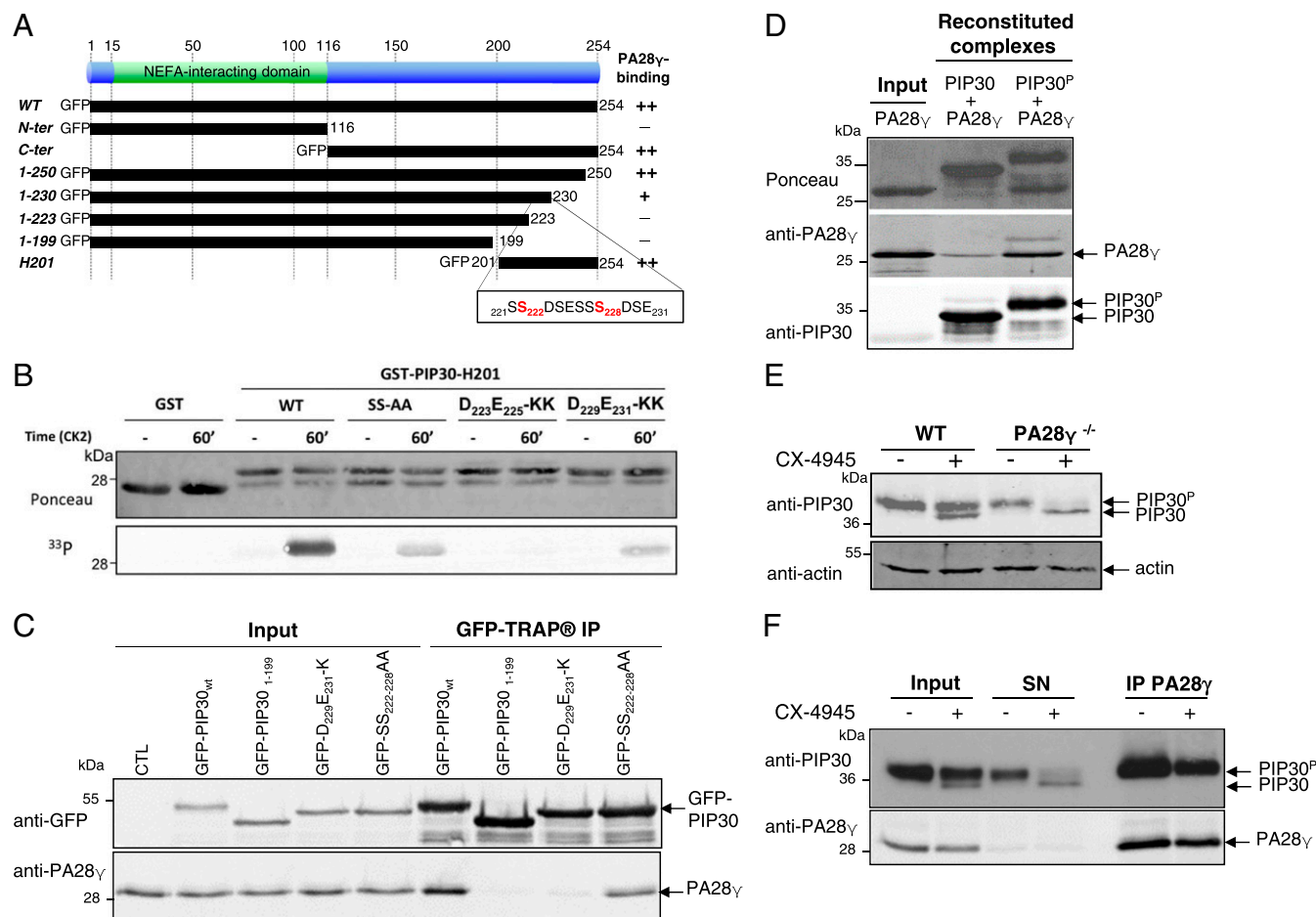


Fig. 2. PIP3 interacts with PA28 γ via its CK2-phosphorylated C terminus. (A) Graphical summary of the analysis of the interaction between several GFP-PIP3 truncation mutants and PA28 γ . (B) The C-terminal end of PIP3 (GST-PIP30-H201) is phosphorylated in vitro by CK2 and point mutations in its CK2 consensus sites strongly reduce its phosphorylation. Purified GST, GST-PIP30-H201, and GST-PIP30-H201 mutants were incubated with CK2, in the presence of [³³P]-ATP for the indicated times. The presence of GST-tagged proteins was revealed by Ponceau staining and their phosphorylation was detected by autoradiography. (C) Point mutations in the CK2 consensus motifs of GFP-PIP30 strongly reduce the interaction between GFP-PIP30 and PA28 γ in cells. U2OS cells were transiently transfected with wild-type or the indicated mutants of PIP30 fused to GFP. GFP-tagged proteins were pulled down using GFP-TRAP beads and the presence of coimmunoprecipitated PA28 γ was assessed by Western blot. Wild-type GFP-PIP30 was used as a positive control and GFP-PIP30₁₋₁₉₉ mutant as a negative control. (D) PA28 γ has more affinity for CK2-phosphorylated PIP3 (PIP30^P) than for unphosphorylated PIP3 in vitro. Bacterially expressed and purified His-PIP30 was either phosphorylated, or not, by CK2 in vitro and then mixed with recombinant PA28 γ . The complex was purified on a Ni-NTA column and analyzed by SDS/PAGE and Western blot with anti-His anti-PA28 γ antibodies. (E) The association between PA28 γ and PIP30 protects PIP30 from dephosphorylation. Wild-type and PA28 γ ^{-/-} U2OS cells were either treated, or not, with CX-4945 (10 μ M) for 24 h and the PIP30 PAGE migration profile was analyzed by Western blot. The phosphorylated form (PIP30^P) and the unphosphorylated form of PIP30 are indicated. (F) PA28 γ interacts with the phosphorylated form of endogenous PIP3 in cells. Endogenous PA28 γ was immunoprecipitated from 500 μ g of total extracts from U2OS cells either treated, or not, with CX-4945 (10 μ M) for 24 h. The presence of coimmunoprecipitated PIP30 was assessed by Western blot. The input and unbound (SN) fractions were also analyzed. After CX-4945 treatment, two bands appear for endogenous PIP30, the phosphorylated form (PIP30^P) and the unphosphorylated form (PIP30), as indicated. CTL, untransfected cells.

degradation of a panel of standard proteasome peptide substrates (38) by the PA28 γ -activated proteasome (Fig. 3A). For example, while the activation of Suc-LLVY-amc (LLVY) and Ac-nLPnLD-amc (nLPnLD) degradation was partially inhibited, degradation of Boc-LRR-amc (LRR) was essentially insensitive to the presence of PIP30 (Fig. 3A and *SI Appendix, Fig. S6A*). The lack of effect of PIP30 on LRR degradation shows that its negative effects on other peptides is not due to alteration of the stability of the 20S proteasome/PA28 γ complex, since the proteasome remains fully activated in this case. Importantly, PIP30 had no effect when PA28 $\alpha\beta$ was used to activate the 20S proteasome or after mutations that prevent its binding to PA28 γ (*SI Appendix, Fig. S6B*). This establishes that the effects of PIP30 on proteasome activities, described in this report, are not direct but require its interaction with PA28 γ , even though it remains

formally possible that PIP30 could nevertheless also affect proteasome functions through undetected labile or transient interactions independent from PA28 γ . The differential effects of PIP30 were not correlated with specific proteasome peptidase activities (Fig. 3A), suggesting that the effects of PIP30 are not a result of alteration of the proteasome active sites. To confirm this hypothesis, we used the proteasome activity probe Bodipy TMR-Ahx₃L₃VS (a generous gift of Huib Ova, Leiden University, Leiden, The Netherlands), which labels efficiently the β 2 (trypsin-like activity) and β 5 (chymotrypsin-like activity) subunits of the proteasome (39, 40). We found that the ratio between β 2 and β 5 labeling was not altered by PIP30 (Fig. 3B), showing that the relative activity of both sites is not changed. Therefore, the differential degradation of LRR (β 2 substrate) and LLVY (β 5 substrate) elicited by PIP30 is most likely due to a differential

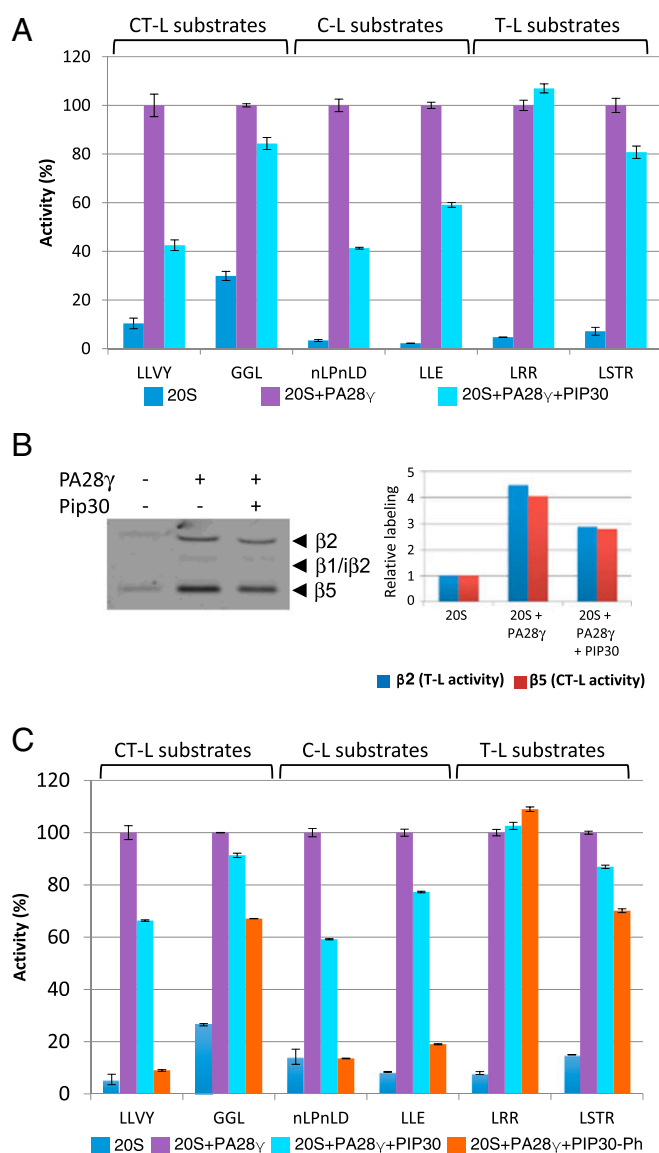


Fig. 3. PIP30 differentially affects peptide diffusion toward the catalytic chamber of the proteasome. (A) Inhibition by PIP30 of PA28 γ -activated 20S proteasome is peptide substrate-specific. Proteasome activity was assayed in the presence of the indicated peptides and proteins and normalized by setting to 100% the value obtained in the presence of 20S proteasome and PA28 γ . The assays were performed for 20 min at 37 °C in a 50- μ L reaction mixture containing the indicated combinations of 20S proteasome (0.5 μ g), PA28 γ (1 μ g), and PIP30 (4 μ g). The respective final concentrations of the 20S proteasome and PA28 γ are set up such as the peptidase activities are not fully activated (i.e., PA28 γ is limiting in the assay). At the final concentration used for PIP30, the inhibitory effect is maximal (SI Appendix, Fig. S6A). Error bars represent deviation from the mean of technical duplicates. The figure is representative of more than three distinct experiments. Peptides used are substrates of the following peptidase activities of the 20S proteasome: Suc-LLVY-amc, Z-GGL-amc: chymotrypsin-like activity; Ac-nLPnLD-amc, Z-LLE-amc: caspase-like activity; Boc-LRR-amc, Boc-LSTR-amc: trypsin-like activity. (B) The activity of the chymotrypsin-like and trypsin-like catalytic sites of the 20S proteasome is not modified by PIP30: 20S proteasome (2 μ g) was mixed in reaction buffer (Tris-HCl 20 mM pH 7.5, DTT 1 mM, glycerol 10%) in a final volume of 18 μ L, with either no protein or with PA28 γ (6 μ g) preincubated for 5 min at room temperature with or without PIP30 (8.3 μ g). After incubation 5 min at room temperature, 2 μ L of the probe Bodipy TMR-Ahx₃L₃VS (1 μ M in reaction buffer) were added to each sample and the mixtures were further incubated 15 min at 37 °C. After denaturation with Laemmli buffer and electrophoresis, the labeled proteasome subunits were visualized (Left) using a Typhoon FLA 7000 (GE Healthcare). The labeling of subunits β 2 and β 5 was quantified and plotted

diffusion rate into the catalytic chamber of the proteasome. This strongly suggests that PIP30 regulates peptide entrance or transit through the channel opened by PA28 γ upon binding to the 20S proteasome.

We next assessed whether PIP30 phosphorylation affects its effect on peptide degradation. Comparing nonphosphorylated and CK2-phosphorylated PIP30 (SI Appendix, Fig. S10D), we found that phosphorylation of PIP30 enhanced its inhibitory effects (Fig. 3C). For the most affected peptides, phosphorylated PIP30 was able to abrogate the activating effect of PA28 γ on their hydrolysis. However, it had a limited effect on other peptides and remained without effect on the basic LRR substrate (Fig. 3C).

Overall, these data show that PIP30 is able to alter the 20S proteasome-activating properties of PA28 γ in vitro. In this process, it seems to act as a phosphorylation-modulated filter that differentially impairs the entrance or the transit of peptide substrates through the PA28 γ channel.

PIP30 Alters PA28 γ Functions in CB Dynamics. We have previously shown that PA28 γ overexpression leads to the disruption of CBs (21), which are evolutionary conserved coilin-dependent and coilin-rich subnuclear compartments. CBs are involved in the maturation of small nuclear ribonucleoproteins (RNPs) and small nucleolar RNPs, as well as in the processing of histone pre-mRNAs (41, 42). We thus tested whether PIP30 has also a role in CB dynamics. First, we compared CB number in wild-type, PA28 γ ^{−/−}, and PIP30^{−/−} U2OS cells. We found that while 80% of wild-type and PA28 γ ^{−/−} U2OS cells display CBs, only 40% of PIP30^{−/−} cells are CB⁺ (Fig. 4A and B). Furthermore, in cells displaying CBs, the absence of PIP30 leads to a decrease in the average number of CBs per nucleus (Fig. 4C). The effect of PIP30 depletion was rescued by expression of GFP-PIP30 (Fig. 4D). Furthermore, the PIP30 mutants impaired in their binding to PA28 γ (i.e., GFP-PIP30_{1–199}, D₂₂₃E₂₂₅-KK, and D₂₂₉E₂₃₁-KK) did not significantly rescue the phenotype, compared with GFP alone (Fig. 4D). Together, these results show that PIP30, like PA28 γ (21), controls the steady-state number of CBs and that this depends on its binding to PA28 γ . However, PIP30 and PA28 γ do not have the same effects in this process. An important question was to assess whether the effect of PIP30 depletion is dependent upon the presence in cells of PA28 γ . We thus compared the effect of PIP30 knockdown in wild-type and PA28 γ ^{−/−} cells (Fig. 4E). The results show that in both cell lines depletion of PIP30 entails a decrease in the number of cells with CBs. However, the effect of PIP30 depletion seems less drastic in PA28 γ ^{−/−} compared with wild-type cells. Together, these results suggest two components in the functions of PIP30 in CB dynamics: one critical that is PA28 γ -dependent, and another that is PA28 γ -independent.

In the absence of PIP30 (i.e., in siRNA PIP30-depleted or PIP30 knockout cells, but not in control cells) we observed an accumulation of PA28 γ in all residual CBs, either identified by coilin (Fig. 5A) or WRAP53 (another CB marker) staining (SI Appendix, Fig. S7A). Furthermore, reexpression of GFP-PIP30 in PIP30-depleted cells abrogated the accumulation of PA28 γ in CBs (SI Appendix, Fig. S7B). These observations demonstrate that PIP30 inhibits PA28 γ subnuclear localization in CBs.

after normalization by the value of their labeling in 20S proteasome alone (Right). In the experimental conditions used, the labeling of both subunits is roughly proportional to their activity. The figure is representative of three distinct experiments. (C) Comparison of the effects of PIP30 and its CK2-phosphorylated form (PIP30-Ph) on the peptidase activities of the PA28 γ /20S proteasome complex. The experiments were performed as in A, except that only 2 μ g of PIP30 and PIP30-Ph were used per assay. Error bars represent deviation from the mean of technical duplicates. The figure is representative of three distinct experiments. C-L, caspase-like; CT-L, chymotrypsin-like; T-L, trypsin-like.

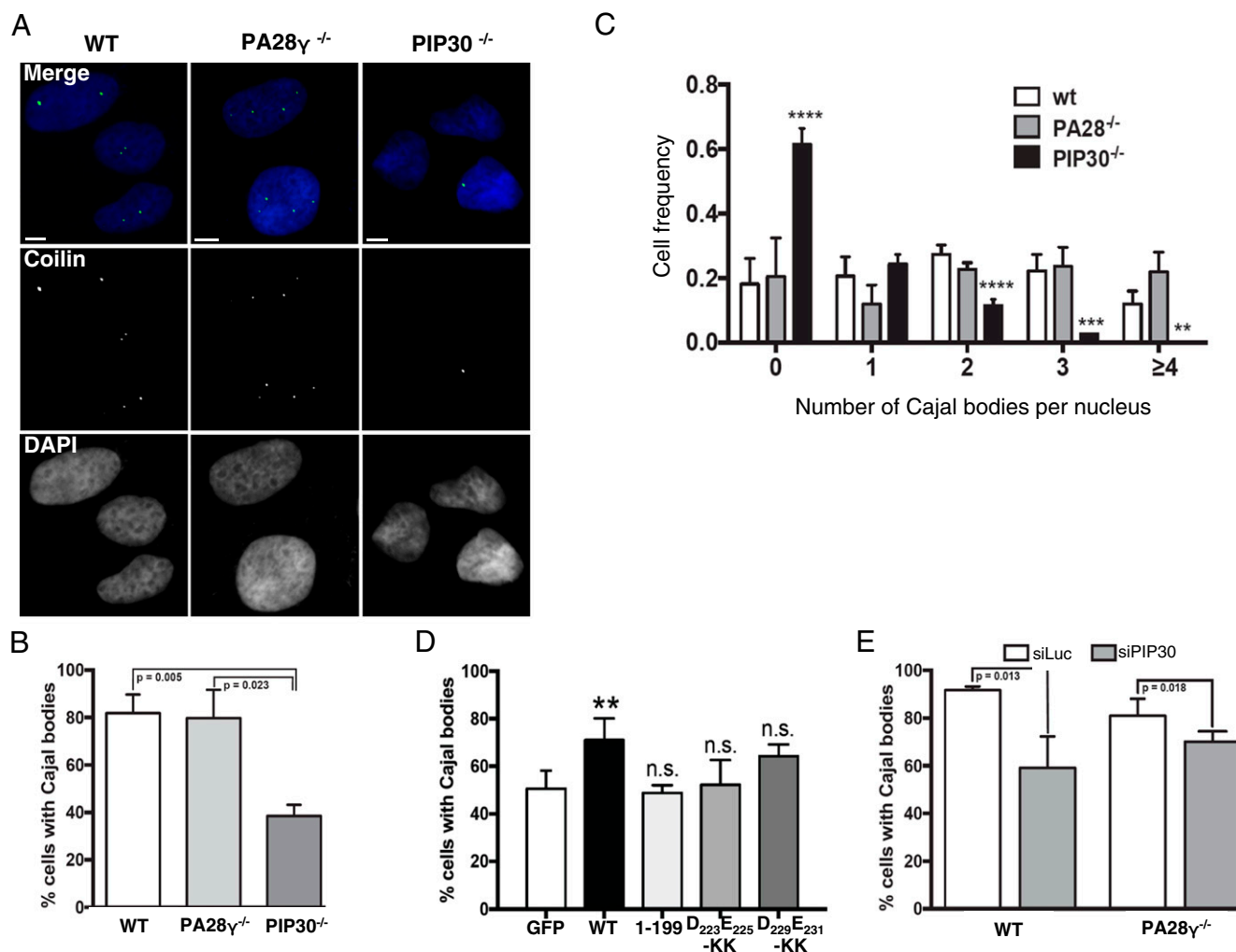


Fig. 4. PIP30 is involved in CB dynamics. (A) PA28 γ and PIP30 depletion have differential effects on CB dynamics. The presence of CBs in wild-type, PA28 $\gamma^{-/-}$, and PIP30 $^{-/-}$ U2OS cells was analyzed by indirect immunofluorescence using 5P10 anticoilin antibody. (Scale bars, 10 μ m.) (B) The coilin signal was used to determine the percentage of CB $^{+}$ cells for wild-type, PA28 $\gamma^{-/-}$, and PIP30 $^{-/-}$ U2OS cells. Data represent the means and SD from three independent experiments ($n = 759$ wild-type, 822 PA28 $\gamma^{-/-}$, and 842 PIP30 $^{-/-}$ cells; $n > 230$ cells per condition per experiment). Two-tailed paired t tests showed a significant difference of PIP30 $^{-/-}$ vs. wild-type U2OS cells ($P = 0.005$). (C) PIP30 depletion induces a decrease in the mean number of CBs per nucleus. The coilin signal was used to quantify the number of CBs per nucleus in wild-type, PA28 $\gamma^{-/-}$, and PIP30 $^{-/-}$ U2OS cells. Data show the percentage of cells displaying 0, 1, 2, 3, or more CBs per nucleus and represent the mean and SD of three independent experiments ($n > 250$ cells per condition per experiment). Asterisks indicate CB frequencies significantly different between mutant and wild-type U2OS cells (multiple t tests): **** $P < 10^{-4}$, *** $P < 10^{-3}$, ** $P < 10^{-2}$. (D) The overexpression of GFP-PIP30, but not of GFP-PIP30₁₋₁₉₉, GFP-PIP30 D₂₂₃E₂₂₅-KK, and GFP-PIP30 D₂₂₉E₂₃₁-KK mutants, defective for PA28 γ binding, rescues the formation and stability of CBs in U2OS PIP30 $^{-/-}$ cells. PIP30 $^{-/-}$ cells were transfected with 100 ng of GFP, GFP-PIP30 wild-type, GFP-PIP30₁₋₁₉₉, GFP-PIP30 D₂₂₃E₂₂₅-KK, and GFP-PIP30 D₂₂₉E₂₃₁-KK plasmids. The percentage of CB $^{+}$ cells was manually determined in each condition by analyzing the presence/absence of coilin dots in all GFP $^{+}$ cells ($n > 30$ transfected cells per condition per experiment). ANOVA analysis of four independent experiments showed significant differences among means ($P = 0.0027$). Only the GFP-PIP30 wild-type showed a significant difference with GFP (Dunnett's multiple comparison test, $P = 0.0055$). (E) The effect of PIP30 knockdown on CB dynamics is attenuated in PA28 $\gamma^{-/-}$ cells. U2OS and PA28 $\gamma^{-/-}$ cells were transfected with 50 nM siRNAs directed against luciferase (siLuc) and PIP30 (siPIP30), during 48 h. The percentage of CB $^{+}$ cells was determined in each condition by analyzing the presence/absence of coilin dots in all cells. Data represent the means and SD from four independent experiments and were analyzed using paired two-tailed t tests ($n > 280$ cells per condition per experiment). n.s., nonsignificant.

Because PA28 γ is known to bind to the key CB component coilin (21) (Dataset S2), we analyzed whether PIP30 could affect this process. We observed that PIP30 depletion led to an increased interaction of PA28 γ with coilin, as seen by co-IP experiments (Fig. 5B). In line with this observation, in the absence of PIP30, an increased number of dots could be seen by PLA using anti-PA28 γ and coilin antibodies, supporting the notion that PIP30 inhibits PA28 γ /coilin interaction (SI Appendix, Fig. S8).

Altogether, these experiments show that PIP30 effect on CBs is mediated through its ability to bind PA28 γ and to counteract PA28 γ association with coilin, confirming that PIP30 indeed functions as an endogenous regulator of PA28 γ .

Discussion

Despite the fact that PA28 complexes have long been known, little is understood regarding their roles as proteasome regulators, besides their ability to open upon binding the gated channel of the 20S proteasome. However, because specific protein substrates have been described for PA28 γ , it is possible that these regulators are not just passively opening the gate of the 20S proteasome but somehow contribute to substrate selection and possibly unfolding and injection into the 20S core. If true, then it is likely that they work in synergy with other proteins, because by themselves they seem a priori unable to actively promote proteasomal

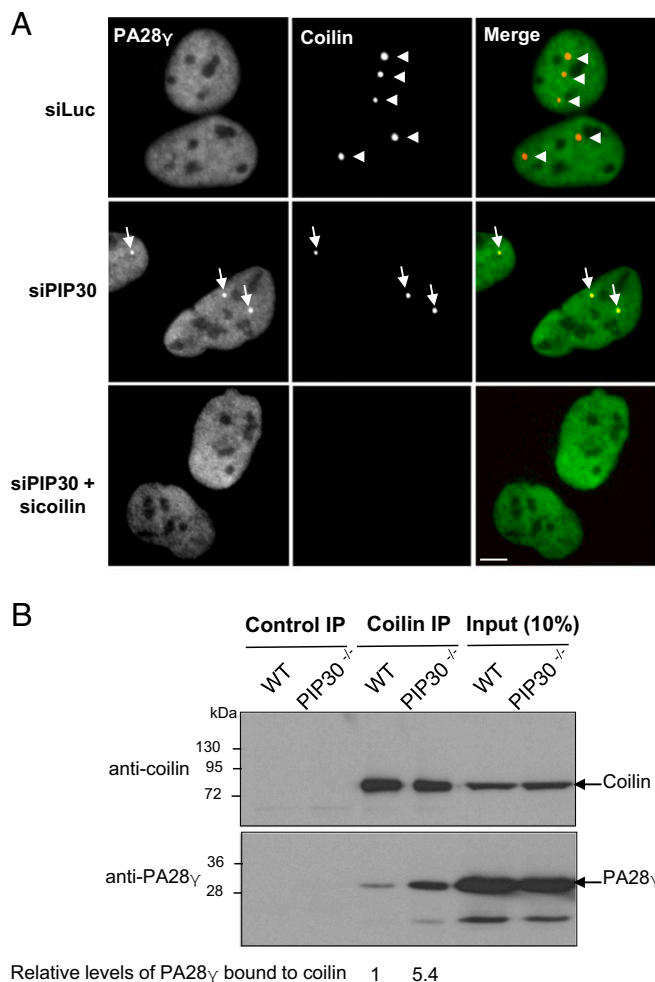


Fig. 5. PIP3O depletion induces accumulation of PA28 γ in residual CBs and enhances the interaction of PA28 γ with coilin. (A) PIP3O depletion induces PA28 γ accumulation in CBs. The colocalization of endogenous PA28 γ and coilin was analyzed by indirect immunofluorescence in U2OS cells treated either with a control siRNA (siLuc), a siRNA targeting PIP3O, or siRNAs targeting both PIP3O and coilin. In the merge panels, the coilin signal is in red and the PA28 γ signal in green. Arrowheads indicate CBs positive for coilin only, while arrows indicate CBs positive for both coilin and PA28 γ . (Scale bars, 10 μ m.) (B) PIP3O depletion increases the level of endogenous coilin coimmunoprecipitated with PA28 γ . Nuclear cell extracts from asynchronously growing parental (wild-type) or PIP3O^{-/-} U2OS cells were incubated with control IgG or anti-coilin antibodies. Immunocomplexes were analyzed by SDS/PAGE, probed for the indicated proteins, and the amount of PA28 γ associated with coilin was quantified and normalized to the amount of immunoprecipitated coilin. The figure is representative of three distinct experiments.

degradation of specific protein substrates. We thus performed various proteomics experiments to characterize proteins associated with PA28 γ .

Among the interaction partners of endogenous PA28 γ , we found several proteins involved in the regulation of RNA processing (Dataset S1), suggesting an important role of PA28 γ in this function. Although PA28 γ interacts with the 20S proteasome, we identified only the $\alpha 6$ subunit (PSMA1) in the conditions used. However, we found most 20S proteasome as well as 19S complex subunits with high H/L ratios when PA28 γ pull-downs were performed with extracts of proteasome inhibitor-treated cells (Dataset S5), confirming both that (i) PA28 γ /20S proteasome interaction is labile (31) and is stabilized upon proteasome inhibition (11, 43), and (ii) PA28 γ , as this has been described for PA28 $\alpha\beta$, can also be

recruited in hybrid forms of the proteasome in which the 20S proteasome is bound to the 19S complex on one side and PA28 γ on the other side.

Importantly, we identified a prominent partner of PA28 γ , PIP30/FAM192A. Interaction between PIP30 and PA28 γ has already been listed in large-scale proteomics experiment data in *Drosophila* and human (44, 45). However, our results validate its biological relevance.

We demonstrated that this interaction is direct and occurs in cells with 20S proteasome-free and -bound PA28 γ . The interaction is specific for PA28 γ because we found no interaction between PIP30 and PA28 $\alpha\beta$ in vitro. This suggests that the interaction may involve the homolog-specific insert, which is the most divergent domain between PA28 paralogs (46). Importantly we show that the PA28 γ -binding region of PIP30 is located in its C-terminal end and that CK2 phosphorylation of a short motif in this region stabilizes its association with PA28 γ . Because mutation of serine residues (S₂₂₂ and S₂₂₈) of both typical CK2 targets does not completely abolish binding, it is likely that additional serine residues are phosphorylated by CK2. This is in line with the ability of CK2 to catalyze the generation of phosphoserine stretches (36), and in agreement with our proteomics analyses (*SI Appendix, Fig. S5*) and with the report that S₂₁₉, S₂₂₁, S₂₂₂, and S₂₂₄ of PIP30 are phosphorylated in vivo [Global Proteome Machine, Accession: ENSP00000335808 (47)]. The role of these multiple phosphorylation events is not clear. CK2 is indeed a ubiquitous and pleiotropic kinase (48), and even if its activity has been shown to be positively regulated by the Wnt/ β -catenin pathway (49) it is considered to be constitutively active in cells. Our results also suggest an extremely slow turnover of the phosphate groups for the majority of PIP30 bound to PA28 γ , probably because steric hindrance makes them inaccessible to phosphatases once the complex is formed. It thus seems unlikely that CK2 phosphorylation of PIP30 is used in cells to dynamically control PIP30/PA28 γ interaction.

Comparison of PIP30 and PA28 γ distributions within the eukaryotic phylogenetic tree (*SI Appendix, Fig. S3B*) shows that their presence or absence is not correlated. For example, in all Ascomycota, including *Saccharomyces cerevisiae*, PIP30 is present while PA28 γ has been lost. This indicates that the two proteins may function independently of each other. However, in human cells, more than 70% of PA28 γ and PIP30/FAM192A are associated in the same complex (*SI Appendix, Fig. S1B*), suggesting that they cooperate in most of their functions.

In line with this assertion, our data show that PIP30 regulates the function of PA28 γ as a proteasome regulator, since its invalidation halves the intracellular level of the PA28 γ /20S proteasome complex (Fig. 1 *D* and *E*). However, because the 20S proteasome/PA28 γ complex only represents $\leq 5\%$ of the total 20S proteasome (29), it is difficult to predict the biological impact of this effect. Based on our *in vitro* analyses showing that PIP30 inhibits the degradation of some peptides by reconstituted 20S proteasome/PA28 γ complexes but is permissive for others (Fig. 3), it is tempting to speculate that PIP30 acts as a molecular sieve that hinders entrance of some protein substrates into the PA28 γ channel while being neutral for others. The likely binding of PIP30 to the PA28 γ -specific insert that forms a loop located close to the pore of the complex (25, 50) is compatible with such a role. Confirmation and further dissection of this hypothesis requires comparison of proteasome- and PA28 γ -dependent substrates whose degradation is differentially regulated by PIP30. Unfortunately, among the several described PA28 γ substrates that we tested, only p21 degradation proved to be PA28 γ -dependent in our conditions, and the cellular stability of this protein turned out to be insensitive to PIP30 presence or absence.

Interestingly, the notion that PA28 complexes could act as a molecular sieve has already been put forward for PA28 $\alpha\beta$, based on detailed studies showing that it selectively filters peptide

products coming out of the proteasome (8, 51). This raises the possibility that PIP30 could, together with PA28 γ , play a selective role not only on substrate entrance but also peptide release by the proteasome.

Taken together, our data are compatible with the interesting hypothesis that binding of PIP30 to PA28 γ could induce a global conformational change of the latter that would both favor its binding to the 20S proteasome and alter its substrate selectivity through alteration of the entrance or the structure of its channel. Structure/functions analyses aiming at precisely mapping the consequences on PA28 γ of PIP30 binding as well as detailed characterization of peptides produced by the proteasome in the presence of PA28 γ and PA28 γ /PIP30 complexes will help to answer these questions.

A second illustration of the role of PIP30 as a PA28 γ regulator is the demonstration that both proteins intimately cooperate in the regulation of CB integrity. Indeed, PIP30 depletion leads to a strong decrease in the number of CBs and to an increased interaction between coilin and PA28 γ (Fig. 5B and *SI Appendix*, Fig. S8A and B). This mimics the phenotype induced by PA28 γ overexpression (21) (*Dataset S2*). PIP30 depletion also elicits the accumulation of PA28 γ in residual CBs, while PA28 γ is usually not detectable in these structures. To our knowledge, PA28 γ has only been observed in CBs of motor neurons from patients with type I spinal muscular atrophy (52). In these pathologic neurons, the assembly of CBs is impaired, due to the lack of the survival motor neuron protein, an essential CB component (53–55). Because CBs are dynamic structures undergoing constant remodeling (56), the accumulation of PA28 γ in residual CBs observed in both PIP30^{−/−} cells and spinal muscular atrophy motor neurons could reflect the fact that these residual CBs are stalled at transient intermediate stages of assembly/disassembly in which PA28 γ is involved. Alternatively, the absence of PIP30 may result in the formation of defective CB structures that are not normally present in wild-type cells. Interestingly, the proteasome is not recruited into CBs, together with PA28 γ , in the absence of PIP30 (*SI Appendix*, Fig. S9A), and proteasome inhibition—which greatly enhances the binding of PA28 γ to the 20S core (11)—inhibits the accumulation of PA28 γ into CBs (*SI Appendix*, Fig. S9B). These observations raise the possibility that the functions of PA28 γ and PIP30 in CBs could be proteasome-independent.

Taking these data together, the effects of PIP30 deletion on CB integrity suggest that increasing the levels of PA28 γ /coilin complexes negatively regulates the number of CBs and that PIP30 inhibits the association between PA28 γ and coilin. This model supports the idea that PA28 γ overexpression leads to CB destabilization by overwhelming PIP30 inhibition, and therefore that the equilibrium between free PA28 γ and PIP30-bound PA28 γ is an important parameter in this process. In this regard, it is interesting to note that CB fragmentation upon UV-C treatment is associated with the concomitant increase in PA28 γ and its recruitment to coilin (21). If PIP30 levels are limiting in cells, the resulting excess of PIP30-free PA28 γ might be sufficient to interact with coilin and induce CB fragmentation.

However, as it is difficult to imagine that PA28 γ functions in CBs could be taken in charge only by neosynthesized PA28 γ that would have escaped definitive PIP30 inhibition, it seems more likely that the binding of PIP30 to PA28 γ can be negatively regulated to favor their dissociation when needed. As mentioned above, our data do not support the idea that such regulation could be mediated only by modulation of CK2 activity or by dephosphorylation of CK2 sites on PIP30. Therefore, we speculate that other regulatory mechanisms, that are yet to be discovered, must be at play to dissociate the PA28 γ /PIP30 complex. Because the interaction zone between PIP30 and PA28 γ is protected against phosphatases, destabilization of the interaction is likely to occur through conformational changes incompatible with further binding. In principle, such conformational changes could be mediated by posttranslational modifications of either PA28 γ or PIP30, or by binding of additional partners or chaperones able to alter upon binding the structure of the complex. Additional work is required to clarify this issue.

Taken together, the results presented here show that PIP30 is an important partner of PA28 γ that regulates its interactome and therefore its functions, for example, by stabilizing its interaction with the 20S proteasome and inhibiting its interaction with coilin. Although most of the data presented in this report show an inhibitory role of PIP30 toward PA28 γ functions, the fact that PIP30 does not influence the PA28 γ -dependent degradation of the protein p21 shows that PIP30 is not a general inhibitor of PA28 γ . In any case, because most PA28 γ is bound to PIP30 in standard cell culture conditions, it is clear that PIP30 must now be taken into account when studying PA28 γ . Although much remains to be understood regarding PIP30 biological functions, our results represent a significant breakthrough because they provide clues on the regulation of PA28 γ /20S proteasome complex, as well as angles of attack to dissect PA28 γ functions and mechanisms of action.

ACKNOWLEDGMENTS. The authors thanks Huib Ovaa (University of Leiden) for proteasome activity probes; Dr. Anne Blangy (Centre de Recherche en Biologie Cellulaire de Montpellier) for critical reading; the rotation students who participated to this work, including Pierre Bercier, Laure Dutrieux, Maryne Franceschi, Jean-Yves Frayssinhes, Anaïs Lugagne, Valentin Pineau, and Haifa Tlaiss; and the imaging facility MRI, member of the national infrastructure France-BioImaging supported by the French National Research Agency (ANR-10-INBS-04, “Investments for the future”). This work was supported by the CNRS, and by funding from the People Programme (Marie Curie Actions) of the EU Seventh Framework Programme FP7 REA agreement 290257, “UPStream” (to O.C.); the comité du Gard de la Ligue Nationale Contre le Cancer, Contract 158484 (to O.C.); the Association pour la Recherche sur le Cancer ARC PJA 20141201831 and 5FI20111203984 (to S.B.); the Wellcome Trust, Grants 097945/B/11/Z and 108058/Z/15/Z (to A.I.L.); and the French Ministry of Research (Investissements d’Avenir Program, Proteomics French Infrastructure, ANR-10-INBS-08) and the Fonds Européens de Développement Régional, Toulouse Métropole, Région Occitanie (fellowships to T.M. and B.F.) to O.B.-S. Support to B.J.-N. was provided by the Marie Curie International Training Network “UPstream.” S.B. was initially supported by European Molecular Biology Organization and Human Frontiers Science Program Long Term Fellowships. This article is based upon work from European Cooperation in Science and Technology (COST) Action (PROTEOSTASIS BM1307), supported by COST.

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